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THE CLIMATE AND PHYSIOGRAPHY OF THE TEXAS COASTAL ZONE

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CONTENTS

THE CLIMATE AND PHYSIOGRAPHY OF THE TEXAS COASTAL ZONE

I. OVERVIEW

Physiographers (e.g., Fenneman and Johnson, 1946) have classified the entire Coastal Zone of Texas as part of the West Gulf Coast Section of the Coastal Plain Province. The immediate Coastal Zone is almost uniformly flat and low with a gradual increase both in height and relief to the north and west. The Coastal Plain Province terminates abruptly at the Balcones Escarpment which generally follows a Del Rio-San Antonio-Austin line. North of Austin, the transition is less abrupt, but follows approximately a line from Austin through Dallas to the Oachita Mountains in Oklahoma.

A significant feature of the Texas Coast is the line of peninsulas and off-shore islands which separates all the major bays, estuaries, and lagoons along the coast from the open Gulf of Mexico. These embayments are important commercial fishery areas in themselves and in addition provide spawning grounds for many commercially important species. Because the off-shore islands restrict tidal exchange, the quantity and quality of drainage from the land surface is of extreme importance to the biota of these bays, estuaries, and lagoons.

The climate of the Texas Coastal Zone is in general subtropical with long warm to hot summers and short mild winters. The average annual temperature (Fig. 1) shows a fairly regular decrease with latitude from about 74° F. at Brownsville to about 70° F. at Sabine Pass. In contrast to the north-south variation of temperature, the average annual precipitation varies from east to west from about 55 inches per year at Sabine Pass to about 26 inches per year at Brownsville (Fig. 2). On the basis of the spatial and seasonal distribution of temperature and precipitation, Thornthwaite distinguishes four climatic belts along the Texas Coast (Fig. 3).

II. REGIONAL CLIMATIC PATTERNS

Upper Coast - The upper coast in this discussion coincides with Thornthwaite's humid zone. In Texas, the zone extends from Louisiana westward to West Galveston Bay.

The climate is predominantly marine. Humidity is high, and precipitation is abundant and fairly evenly distributed throughout the year although there is a slight maximum in the summer. This summertime maximum may be attributed to local convective activity associated with the sea breeze circulation and tropical disturbances from the Gulf of Mexico.

During the summer, afternoon temperatures are typically lowered along the coast by the sea breeze which is an on-shore wind resulting from temperature differences between the land and sea surfaces. Frequently convergence in the low-level wind field caused by the sea breeze circulation leads to afternoon and evening rain showers.

Winters are typically mild. Invasions of cold continental air masses usually last only two to three days depending on the intensity of the system before the mild southerly air-flow which prevails in this season returns bringing warmer temperatures. The climatological expectation is for from five to ten days during the winter with temperatures 32% F. or below. The mean date of the first freezing temperature is December 15, while the mean date of the last freezing temperature is February 15. Snow is rare, with the mean annual snowfall less than one inch. Spring and Fall in this zone generally resemble the summer climate with occasional cooler periods resulting from invasions of modified polar air masses.

Middle Coast - The middle coast extends from western Galveston Bay to southern Corpus Christi Bay. Thornthwaite (Fig. 3) distinguishes *two climate types, wet subhumid and dry-subhumid,* in this zone however, this distinction is based mainly on total precipitation. The climate in this zone becomes progressively drier and more continental toward the west and south. The precipitation regime here is more characteristic of that in most of the interior of the State, that is, there is a maximum of precipitation in thé late spring with a secondary maximum in early fall. The average annual precipitation in this zone decreases fairly regularly to the west from about 46 inches to about 34 inches (Fig. 2).

Mainly because of the irregularity of the coastline in this zone and the barrier islands, the sea-breeze circulation in summer is less well developed here than on the upper coast, although it does have significant cooling effects near the shoreline. Convective activity associated with the sea-breeze circulation contributes less to the summer rainfall in the area so that the May-September maxima common to the interior are evident in the average annual distribution of rainfall.

Cold air masses traversing this area in late fall, winter, and early spring are usually considerably modified by the time they reach the coast. Mean annual number of days with temperatures of 32% F. or below is about five or less. On the average, freezing temperatures occur between December 15 and February 15 in common with the upper coast. Snow is rare. The climatological expectation of days with temperatures of 90% F. or above rises to about 90 per year in this area in contrast with only about 60 days per year in the upper coast zone.

Lower Coast - The lower coast extends from southern Corpus Christi Bay to the Rio Grande. Thornthwaite (Fig. 3) classified the climate *as semi-arid.* Average annual precipitation ranges from about 34 inches along the coast in the north to about 26 inches at the mouth of the Rio Grande (Fig. 2). Precipitation decreases fairly rapidly inland to the west so that Mission only about 50 miles from the coast along the Rio Grande has an annual average of less than 20 inches. The monthly distribution of precipitation in this area exhibits maxima in May and September.

Summers are long, hot, and relatively dry in this zone. The slight cooling effect of the sea breeze circulation, and the small amount of summer cloudiness in this area are evidenced by the fact that the mean annual number of days with maximum temperature of 90% F. and above is about 90 near the coast but increases to 120 or more about 50 miles inland. Spring and Fall resemble Summer here, with more rain and slightly more moderate temperatures.

Winters are short and mild. The mean length of the freeze-free period in this zone is about 330 days. Freezing weather occurs on the average from less than two days in the south to about five days per year in the north part of the lower coast. Cold air masses which penetrate as far south as the lower coast in winter are much modified in passage so that temperature changes in this zone are much less pronounced than those in the Austin area for example. Only about once in ten years on the average do cold outbreaks severe enough to damage winter crops and fruit trees occur in this area.

III. HURRICANES

Historical Patterns - Hurricanes have struck the Texas Coast throughout history, some with disastrous results. There is no reason to believe that there will be any striking change in either the frequency or the pattern of future hurricanes affecting Texas (Fig. 6). The frequency with which hurricanes strike Texas shows considerable variation, there have been hurricane-free periods of up to six years (1903-1908) followed by years of higher frequency. In both 1933 and 1942 two hurricanes struck Texas. *Based on the record from 1900 to the present, it can be expected that on the average, a hurricane will strike somewhere on the Texas Coast about once in two years.*

Hurricanes which affect Texas form in the southern North Atlantic, the Carribean Sea, and the Gulf of Mexico. The most favorable location for formation of these hurricanes varies from month to month in the hurricane season which extends from June through October. Hurricanes occasionally form in the period November through May, but none are known to have affected Texas in these months. About two-thirds of the hurricanes which have struck Texas have occurred in August and September, while the remaining one-third have occurred in June, July, and October.

Hurricanes develop from easterly waves in the zone of convergence between the northeast and southeast trade winds which is located as much as twelve degrees north of the equator in August. Easterly waves are common in the tropics. An easterly wave will pass a given station in the trade wind belt twice a week on the average. Most easterly waves are stable and may travel thousands of miles with no further development, but occasionally, when conditions are favorable, an easterly wave will become unstable and will intensify further becoming a tropical cyclone.

Tropical cyclone is the generic term for all cyclonic circulations developing over tropical waters. Four stages in the development of a tropical cyclone are distinguished: *tropical disturbance, tropical depression, tropical storm, and hurricane.* The stages are marked by increasingly well organized rotary circulation and higher wind speeds (Fig. 7). A hurricane, for instance, has pronounced rotary circulation and maximum winds of *74 miles per hour* or more.

A tropical cyclone on reaching land or recurving over the cooler water of the North Atlantic may dissipate, or it may take on extra-tropical characteristics and continue its path of destruction far to the north. All tropical cyclones have the potential for producing extreme rainfall when passing inland; the hurricane, of course, being the most intense stage of tropical storm development, poses the additional threat of damage from high tides, wind, and tornados.

IV. HURRICANE DESTRUCTION

Tides and Wave Action - By far, the greatest destruction and loss of life along the Texas Coast have resulted from a *combination of hurricane tide and wave action.* As a hurricane approaches the coast, water is piled up to the right of the hurricane's path by the on-shore wind (Fig. 4). When coupled with astronomical high tide and the rise in water level because of the low atmospheric pressure within a hurricane, abnormally high tides of the order of *15 feet* may be produced on the open coast (Fig. 5). Still higher tides have been observed in bays along the coast.

A particularly destructive feature of some hurricanes is the *storm surge* the explanation of which is not well understood. The storm (or hurricane) surge is a rapid rise in water level of several feet in a few seconds which coincides approximately with the arrival of the center of the storm. During the September 8, 1900, hurricane at Galveston in which about 6,000 lives were lost, Dr. I. M. Cline who was then in charge of the Weather Bureau at Galveston describes a *sudden rise of water level of four feet in as many seconds.*

Wind - Representative wind readings during hurricanes are scarce for several reasons. Even if wind instruments are installed in an area where a hurricane strikes they usually fail before maximum wind speeds are reached. Most wind instruments which are strong enough to withstand hurricane winds have considerable inertia and do not indicate gusts accurately. Tests with specially installed "gust meters" have indicated that hurricane gusts may exceed the steady wind by 50 percent, thus in a steady 150 m.p.h. wind, gusts might reach 225 m.p.h.. In spite of the lack of data it seems likely that most hurricanes have steady winds of 100 m.p.h. at some time in their life cycle, 150 m.p.h. winds are not uncommon, and in some extreme cases winds have exceeded 200 m.p.h..

The force exerted by the wind on a structure increases as the *square of the wind speed.* Engineers have estimated that while a 60 m.p.h. wind exerts a force of 15 pounds per square foot, a 150 m.p.h. wind exerts 112 pounds per square foot. Actual force on a structure may exceed one and a half times the direct frontal pressure, depending on the shape of the structure, because of negative pressure on the leeward side.

Added to the dynamic force of the wind is the *energy contained in heavy, wind-blown debris* which may damage or destroy a building which could otherwise withstand the wind pressure. Flying debris has been responsible for many deaths and injuries in past hurricanes. Fortunately, the windspeed in most hurricanes decreases rapidly as the storm moves inland. Hurricane Celia (August, 1970) was a notable exception in that not only did most of the damage in the coastal area result from high winds (maximum reported 161 m.p.h.), but it still produced 90 m.p.h. gusts as far inland as Del Rio.

Flooding - Next to wave and tide action, hurricane floods are the second greatest source of deaths, injuries, and damage. As a hurricane moves inland, the winds tend to be retarded by surface friction and to blow more directly inward toward the storm center thus increasing low-level convergence and the rainfall rate. When the vertical motion induced by the increased convergence is added to lifting by higher terrain or a frontal surface, torrential rains can result. *Twenty to thirty inches of rain* during the passage of a dissipating hurricane are not unusual. While this amount of rainfall in a period of a few days may produce long-lasting high water in flat, low flying areas near the coast, only water damage to buildings, furnishings, crops, and equipment usually result with much inconvenience but little loss of life among the inhabitants. But in hilly or mountainous regions catastrophic floods may result with heavy flood damage and great loss of life. Runoff from hurricane rains may greatly decrease the salinity of coastal embayments temporarily.

Hurricane Beulah (1967) is an example of a hurricane producing widespread and extensive damages from flooding. While two other Texas storms have produced higher rainfall rates (Hearne, June, 1899 - 24 inches in 24 hours; and Thrall, September, 1921 - 38.2 inches in 24 hours), Beulah stands alone when the extent of heavy rains is considered (Fig. 9). All Texas streams from the Nueces south and west to the Rio Grande and streams in northeast Mexico experienced flooding following the passage of Beulah. Floods on many of these streams were greatly in excess of previous record floods. Fortunately, Beulah turned to the south and west after crossing the coast rather than following the more normal path to the northeast which would have taken it through the more densely populated and highly developed central and northeastern portions of Texas in which case damages and loss of life would likely have been even greater.

Hurricane Tornados - Tornados are frequently reported in association with the passage of hurricanes. It is likely that many tornado occurrences are unobserved amid the general destruction of a hurricane passage. Study of hurricane tornados indicates that they occur only in the forward semicircle or along the advancing periphery of the storm and that they are generally less severe than the usual inland tornado with a shorter and narrower path.

Hurricane Beulah was also unique in the number of reported tornados. The E.S.S.A. State Climatologist for Texas has confirmed reports of *115 tornados* associated with this storm from areas as widely separated as Houston and Austin. The most severe of these occurred at Palacios where three persons were killed and five were injured.

V. HURRICANE PROTECTION

Existing Protection - Hurricane protection work along the Texas Coast has taken the form of protection from storm tides and waves by *sea walls* and *levees*, and by *drainage structures* to lessen damage from flooding. No protection is offered against hurricane winds and tornados although experience in other states has demonstrated that strict building codes in hurricane prone areas can reduce wind damage significantly.

The *Galveston Sea Wall* was the first protective structure to be constructed along the Texas Coast. It was constructed following the disastrous hurricane of 1900 and has since been improved and extended to offer additional protection to the city. Other hurricane protective structures are located at Port Arthur, Texas City-La Marque-Hitchcock, Corpus Christi, and at Freeport. Other small scale protective works exist but are probably inadequate for protection in a severe hurricane.

Future Plans - Historically, hurricane protective work has had to wait on development along the coast line and usually on the passage of a destructive hurricane through a highly developed area. However, the U. S. Army Corps of Engineers is presently investigating the feasibility of providing hurricane protection to the *entire coast of Texas* by erecting levees along the beaches and the barrier islands with secondary protective structures to protect developed areas along the inshore bays. These studies are scheduled to be completed in 1973.

It seems likely at this time that protection of the entire coast of Texas will prove *infeasible* from the standpoint of expected benefits and costs along many thinly populated sections of the coast, but the plan could serve as a guide for a future integrated protective system of the entire coast as development occurs.

Hurricane Warnings - Modern communications and surveillance of hurricanes by aircraft, radar, and satellites coupled with improved forecast techniques have greatly increased the time available to prepare for a hurricane. Such preparation may include mass evacuation of the threatened area, for instance, in Hurricane Carla (1961) an estimated 350,000 persons fled inland from the coastal areas of Texas and Louisiana. There is no doubt that the evacuation greatly reduced the death toll.

Especially needed in this connection is a foolproof forecast technique. Preparation for a hurricane in a highly developed area can be very costly, but of necessity, hurricane warnings are issued for larger areas than actually prove necessary to allow for last minute changes in path thus requiring some areas to prepare unnecessarily. Many scientists are studying the problem and better understanding of the *process of tropical cyclone genesis* will probably lead to improved forecasts and possibly to reduction of the intensity of hurricanes which threaten coastal areas by some form of weather modification.

VI. *CHARACTERISTIC GULF CURRENTS*

Locations and Directions - The semi-permanent off-shore currents along the Texas Coast are governed by the main stream of the North Equatorial Current which enters the Gulf of Mexico through the Yucatan Channel. The eastern part of this flow turns to the right to flow out through the Florida Strait. The western part divides into two currents, one of which flows westward along the upper coast of Texas while the other flows to the north along the lower coast. These two currents meet along the central coast of Texas in a convergence zone which is locally known as the *whirlpool of the Gulf*. The two semi-permanent along-shore currents along the Texas Coast as well as the convergence zone remain fairly constant from year to year, but shift in location and relative strength in response to seasonal changes in the prevailing wind. Winds and tides resulting from hurricanes and other tropical cyclones have only a transitory effect on these semi-permanent currents.

Seasonal Variations - Off-shore currents off Sabine Pass are to the west and those off the Rio Grande are to the north throughout the year. Winds influence only intensities and minor changes in direction of these currents and the location of the convergence zone.

During January, February, and March, the westward and southwestward current is well developed in response to the prevailing easterly winds during this season. The convergence zone is located off Aransas Pass. In May the winds shift to southeasterly and the northerly current off the lower coast extends further north shifting the convergence zone along the coast to the vicinity of the mouth of the Colorado River. This condition prevails during the summer with the northerly current along the lower coast reaching its greatest development. In September, the prevailing winds shift abruptly to the east and the convergence zone shifts to the southwest off Corpus Christi Bay. In the winter, the southwest nearshore current along the upper coast reaches its greatest development at the time when the prevailing winds have their most northerly component.

Performance as Pollutant Dispersers - Because the prevailing currents along the Texas Coast have an alongshore and in some cases an onshore component they function poorly as dispersers of pollutants. Alongshore currents carry sediments from the Mississippi, which drains most of the interior of the continent, for considerable distances along the Texas Coast. In these sediments, one finds much of the waste materials produced in the Central United States. Mississippi sediments have been identified as far to the west as the continental shelf off Rockport. It is reported that Rio Grande sediments are transported as far north as the Rockport vicinity, but there is some disagreement as to the extent of northward transport.

Surprisingly, in view of the importance of the Gulf of Mexico to the United States, Mexico, and Cuba, *little is known in detail of the ocean currents and circulation*. Since about two-thirds of the United States and more than half of Mexico contribute sediments - *and pollutants* - to the Gulf of Mexico, studies of ocean currents, circulation, and the effects of pollutants on the biota of the Gulf should have high priority.

VII. PHYSIOGRAPHIC FEATURES

Water Courses and Deltas - Texas is drained by ten major river systems which enter coastal bays, estuaries, and lagoons or empty directly into the Gulf along the Texas Coast. In order, from northeast to southwest, these are: the Sabine, Neches, Trinity, San Jacinto, Brazos, Colorado, Guadalupe, San Antonio, Nueces, and Rio Grande. In addition to these major systems, there are many minor coastal drainage systems which feed into the Gulf or the coastal embayments. Of the major streams, only the Brazos, Colorado, and Rio Grande empty directly into the Gulf. The Rio Grande normally has little or no flow at its mouth because of heavy demands in its lower reaches for municipal, industrial, and irrigation water.

Little delta building is presently taking place along the Texas Coast. There are many factors which influence this lack of delta building including the prevailing alongshore currents off the Texas Coast and the many upstream dams on Texas streams which considerably reduce the sediment load reaching coastal waters. In the case of rivers emptying into coastal embayments, the river water tends to ride over the denser saline water in the bays so that sediments are well distributed within the bays by local currents. The Trinity delta, for example, has built forward only approximately three tenths of a mile since 1855.

The most spectacular delta building episode occurred on the Colorado which had been dammed by a log jam prior to 1926 when the log jam was gradually cleared. Between 1930 and 1936, the Colorado delta built forward *four miles* across Matagorda Bay cutting the bay into two arms. The Colorado now has a direct exit into the Gulf. It is believed that the majority of the sediments used in the rapid delta building sequence had previously been trapped behind the log jam.

Estuarine and Beach Areas - The Texas Coast is an almost continuous series of bays, estuaries and lagoons from Sabine Lake through the Laguna Madre. The central depths of these embayments range from about four to thirteen feet except for areas near inlets, where local tidal currents may scour holes 30 to 40 feet deep, and dredged channels. The average rate of deposition in these bays is on the order of about *one foot per century* so that these embayments may be eliminated in less than a millenium unless there is a rise in sea level. Indications are that the Brazos River has already filled its bay. It now flows directly into the Gulf.

Texas bays penetrate about 30 miles inside the outer coast to the "bay line" where the gentle slope of the coastal plain limits inland progress of the bays. The bays are generally flanked by alluvial plains which in their lower ends are marshy in most places. Inside the bays there are fluvial plains flanking the river valleys. Seaward of the bays, there are barrier islands and barrier spits which protect them from the open Gulf. The shores of many bays, as well as the open coast and both sides of the barrier islands and spits have many miles of fine sandy beaches which provide excellent recreational areas.

VIII. IMPACTS ON DEVELOPMENT

Climate's Impact - The mild climate of the Texas Coast and the long frost free period have favored *agricultural* development. Crops range from rice, which requires large quantities of water, along the Upper Coast to forage in the drier sections. The Lower Rio Grande Valley where irrigation water is available produces large and varied crops mainly of fruit and vegetables as do other smaller areas in the lower and middle coastal zones. The climate of the Coastal Zone which permits outdoor activities year-round is attractive to *industry*, and an increasing *recreation*-based development is taking place in the area.

The main climatic hindrance to development is the threat of hurricanes, but the proximity to raw materials in the case of the petrochemical industry and other factors have outweighed this threat in many cases especially in areas where hurricane protection has been provided by sea-walls and levees.

Influence of Physiography - The coastal environment has led to the development of several major deep-draft ports along the Texas Coast. For this reason, among others, many industries which require access to world *shipping* lanes have located on the Texas Coast. An important *fishing* industry has developed in the area, and the proximity to both fresh water lakes and the bays and open Gulf attracts an increasing number of boating and sports-fishing enthusiasts each year. *Hunters* attracted to the coastal salt marshes, which are major wintering and breeding grounds for northern waterfowl, provide an important source of revenue.

Air Pollution - Air pollution along the Texas Coast has not previously been a widespread serious problem although local, temporary pollution episodes occur. Two factors have been responsible for the relative freedom from air pollution problems to date. First is the almost *universal use of natural gas* by industry in the Coastal Zone and little use of other less clean burining types of fuel. The other factor is the *naturally less stable stratification* of the lower atmosphere over the Texas Coast coupled with higher average surface winds which cause pollutants to be mixed throughout a deeper layer of the atmosphere than in air pollution prone areas.

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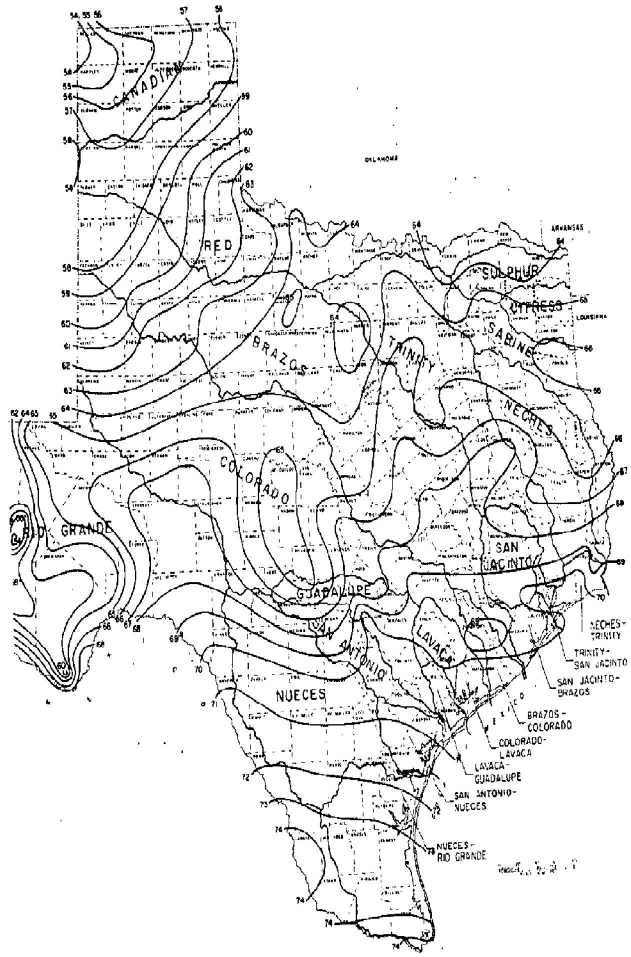
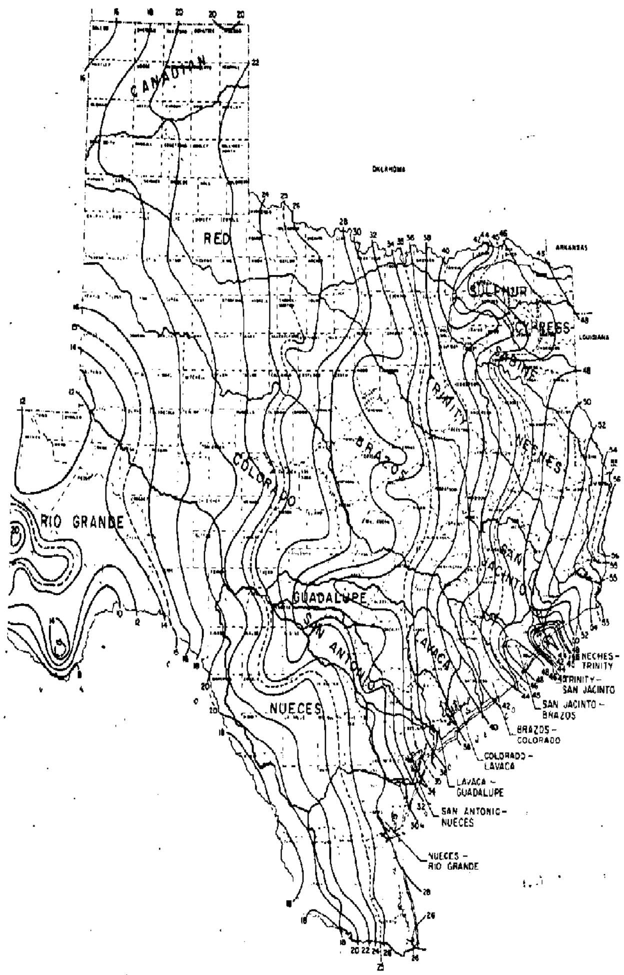


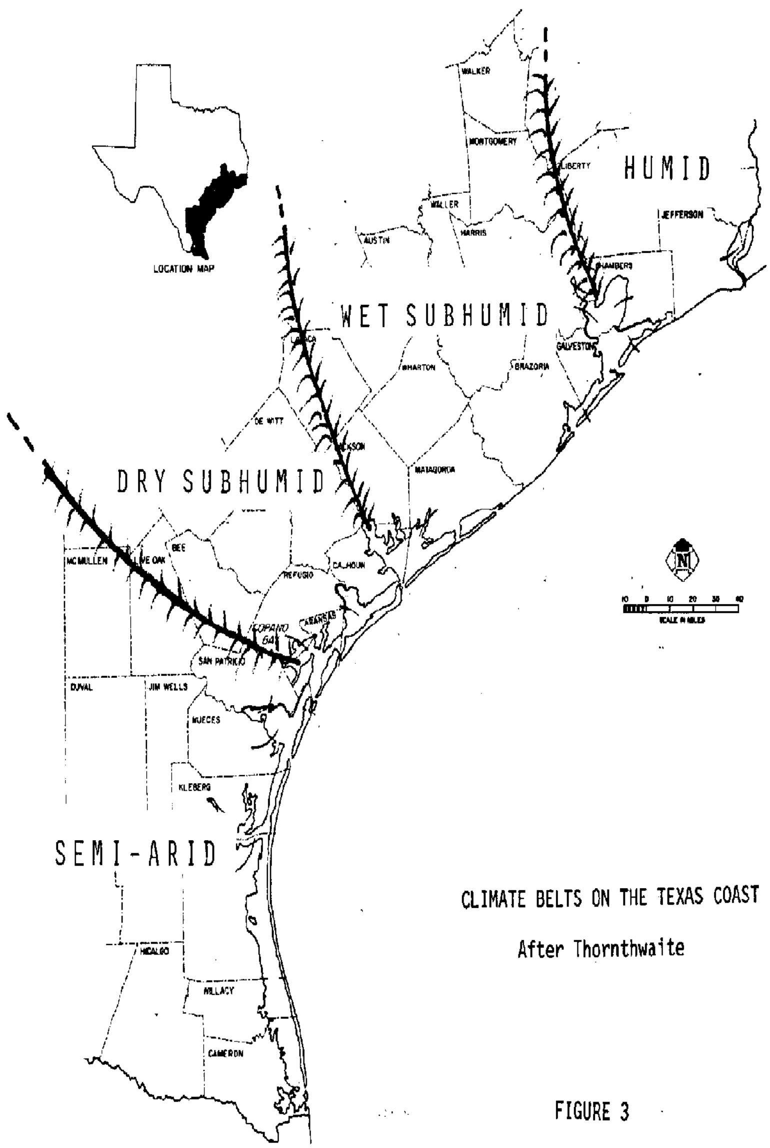
Average Annual Mean Free-Air Temperature (Degrees Fahrenheit) 1931-60

FIGURE 1



Average Annual Precipitation
in Inches 1931-60

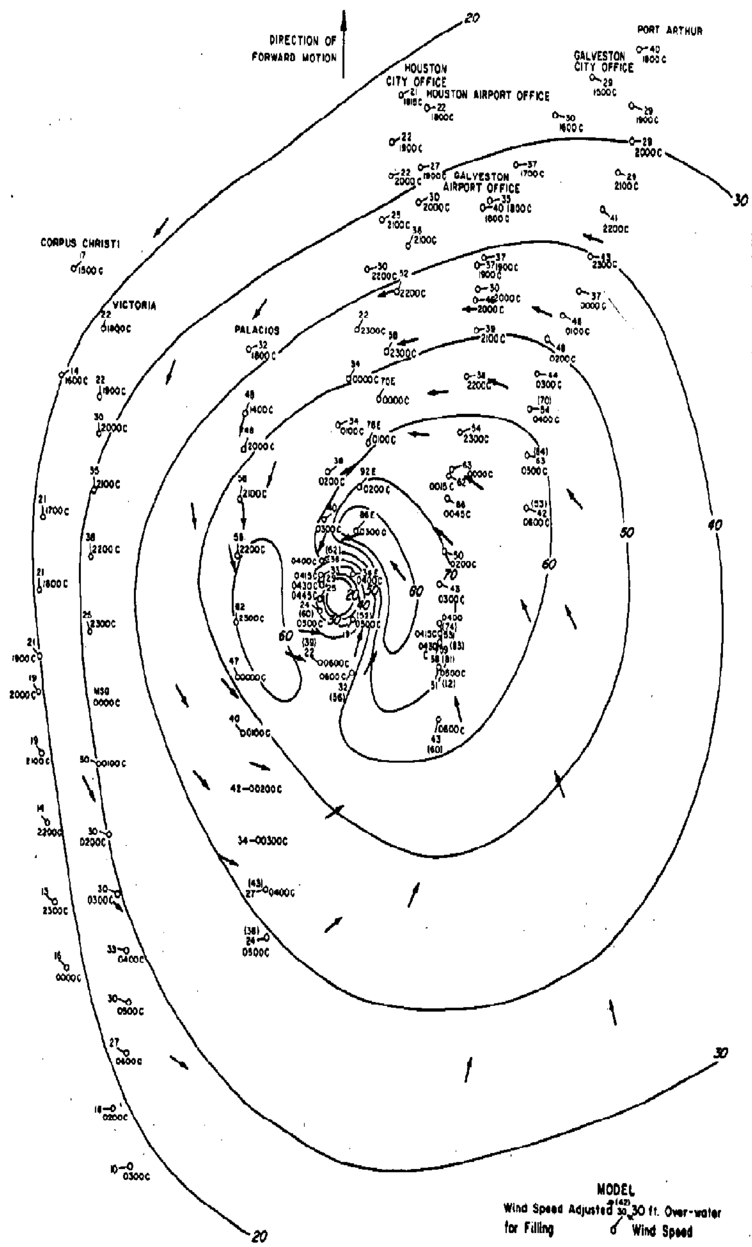
FIGURE 2



CLIMATE BELTS ON THE TEXAS COAST

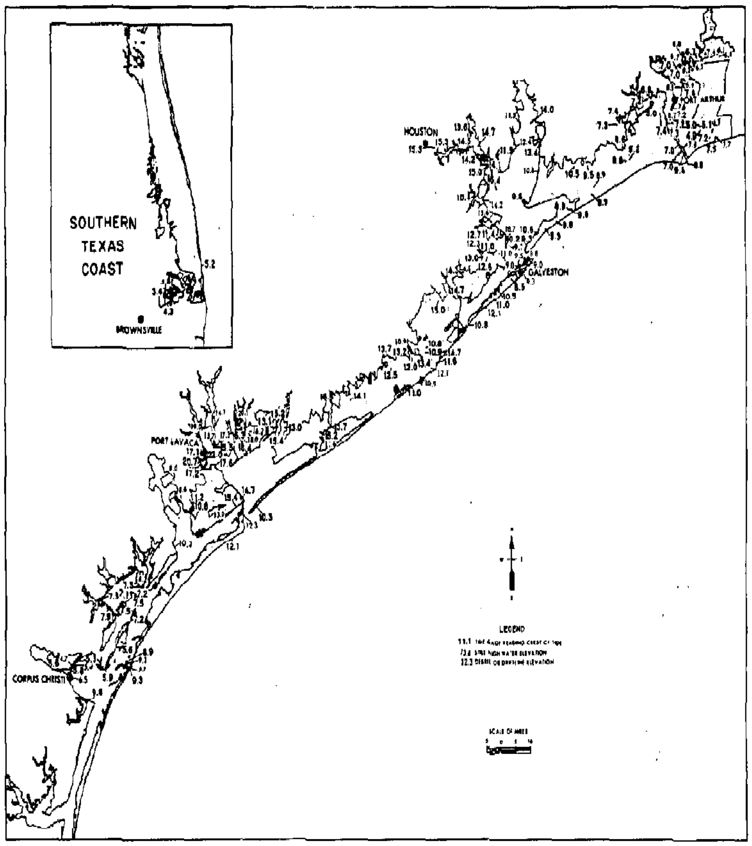
After Thornthwaite

FIGURE 3



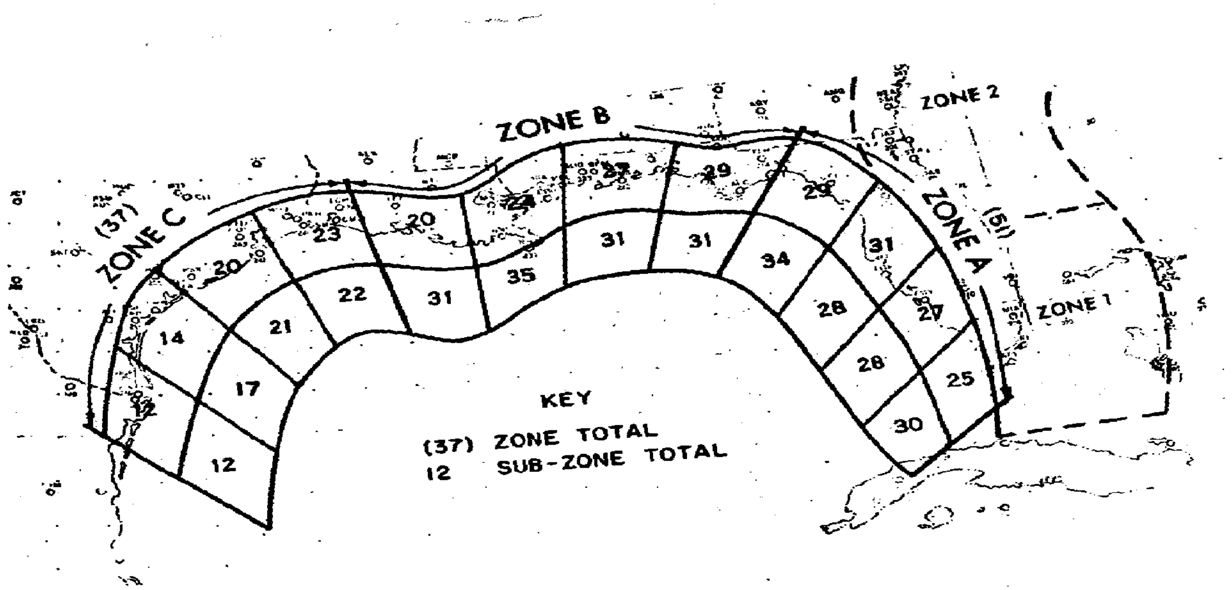
--Composite Wind-Speed and Direction Pattern, October 3, 1949, Near the Texas Coast. All times CST. Speeds in mph adjusted to 30 feet above water.

FIGURE 4



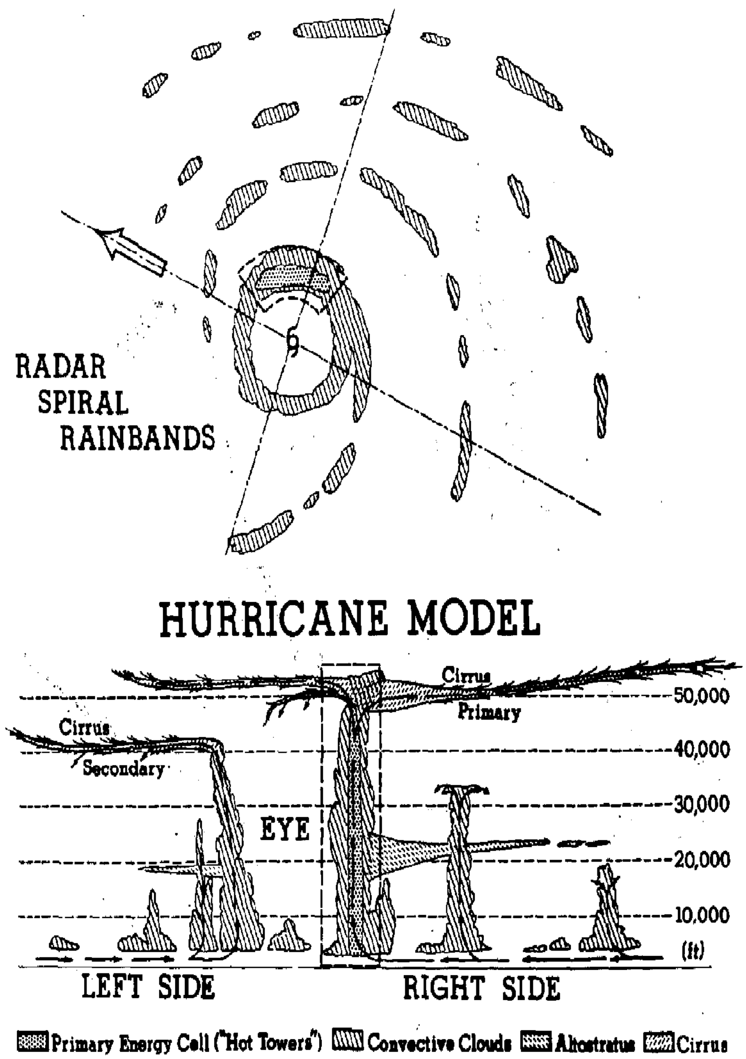
-Hurricane Carla, September 7-12, 1961. High water mark chart for Texas. Shaded area indicates the extent of flooding. (Based on data obtained from the Galveston District of the U.S. Army Corps of Engineers.)

FIGURE 5



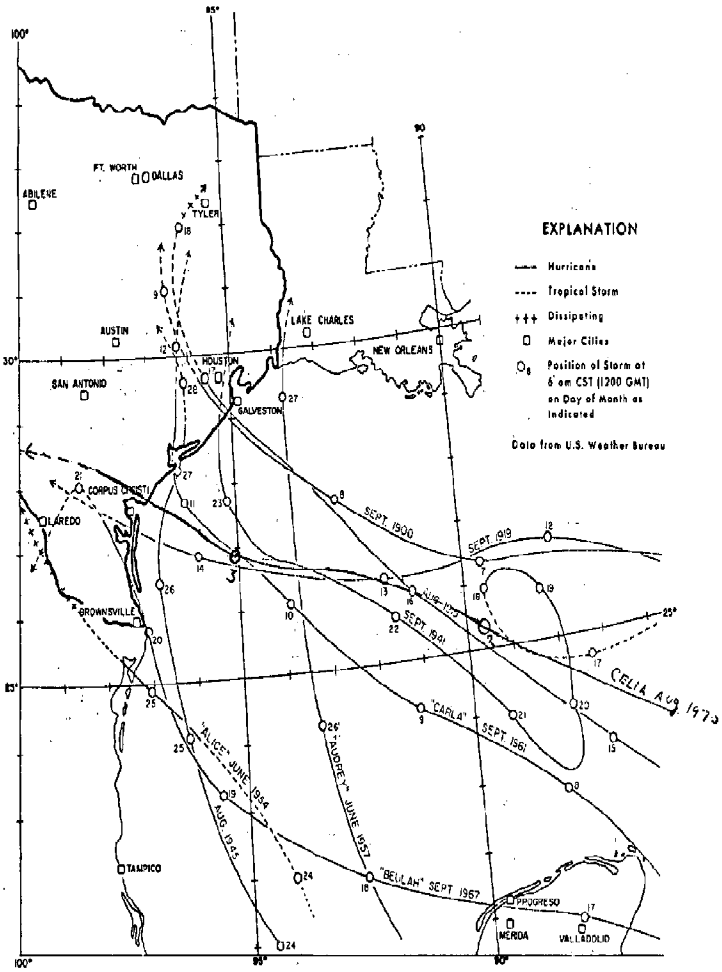
Gulf Coast Zone Subdivisions Showing Total Hurricane Occurrences 1900-1956

FIGURE 6



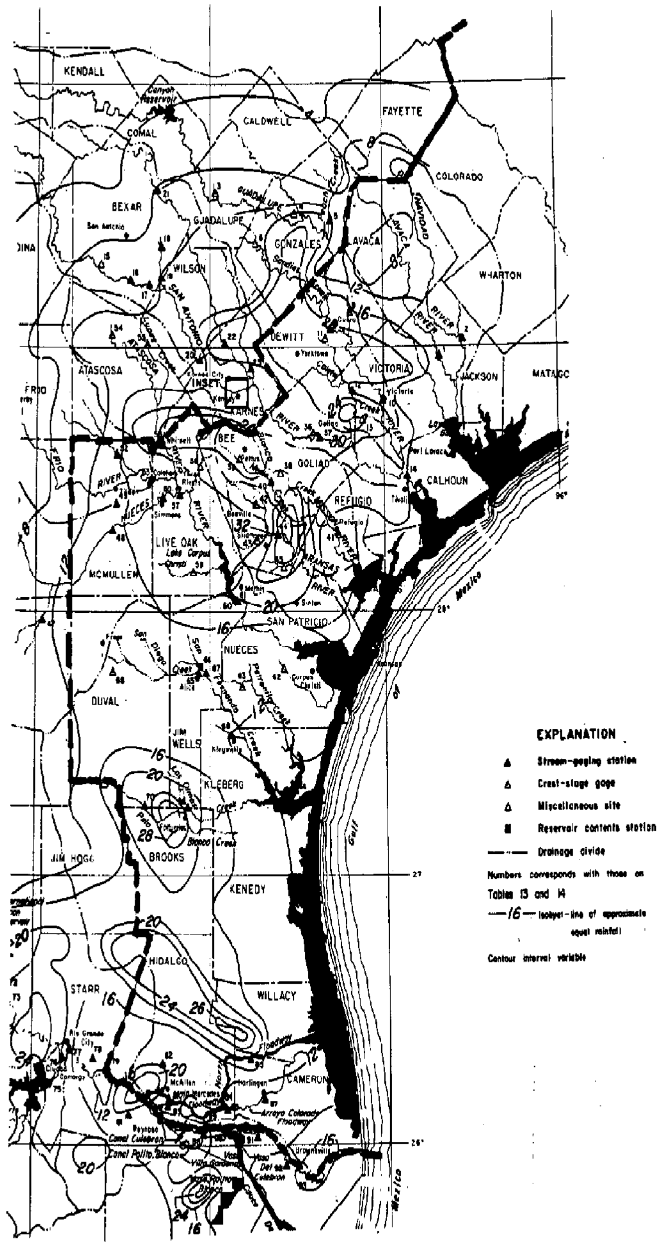
- The Hurricane Model. The primary energy cell (convective chimney) is located in the area enclosed by the broken line. (From NHRP Rept. no. 60, Hurricane Esther 1961.)

FIGURE 7



MAJOR HURRICANES
1900-1970

FIGURE 8



RAINFALL RESULTING FROM HURRICANE BEULAH

FIGURE 9